

# SIRAS-G: The Space-based Infrared Atmospheric Sounder from Geosynchronous Orbit

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**Abstract.** The Spaceborne Infrared Sounder for Geosynchronous Earth Orbit (SIRAS-G) represents a new approach for imaging spectrometry in the infrared suitable for Earth observation from both low-Earth and geosynchronous orbit. SIRAS-G, selected for development under NASA's 2002 Instrument Incubator Program (IIP), is an instrument concept of lower mass and power than contemporary instruments offering enhanced capabilities for atmospheric temperature, water vapor, and trace gas column measurements. At the core of SIRAS-G are modular grating spectrometers that provide high spectral resolution with high spatial resolution. Both the spectral range and resolution of these spectrometers can be modified to match science measurement needs. The flight instrument concept is intended for atmospheric sounding, using 2048 spectral channels, with a nominal spectral resolution ( $\lambda/\Delta\lambda$ ) of between 700 and 1500. SIRAS-G's well-corrected wide field of view optical system minimizes spectral smile and keystone distortion. A technology demonstration instrument including telescope, a single spectrometer leg, large-format focal plane and an active cooling subsystem is being designed, assembled and tested are part of this program. Current progress on the SIRAS-G program is described, including status on the design and build of the demonstration instrument. Several candidate scientific missions are discussed, demonstrating the broad utility of this instrument concept.

## I. INTRODUCTION

The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G) is an instrument concept designed to provide highly accurate atmospheric temperature and water vapor profile measurements from geosynchronous orbit (GEO) to facilitate weather forecasting, severe storm tracking, and scientific research. The baseline flight instrument concept measures infrared radiation in 2048 channels extending from  $3.3\mu\text{m}$  to  $14.8\mu\text{m}$  with a spectral resolution ( $\lambda/\Delta\lambda$ ) of 1200. SIRAS-G employs a wide field-of-view hyperspectral infrared optical system that splits the incoming radiation into four separate grating spectrometer channels. This allows for slow scanning of the scene, increased dwell time, and improved radiometric sensitivity. Unlike competing technologies, such as Fourier Transform Spectrometers (FTS), SIRAS-G employs no moving parts or metrology lasers, leading to improved system reliability over mission lifetime.

SIRAS-G follows the successful completion of the 1999 NASA-sponsored SIRAS (Spaceborne Infrared Atmospheric

Sounder) Instrument Incubator Program [1], in which the 12- $15.4\mu\text{m}$  spectrometer module was developed. SIRAS-1999 was focused on developing the spectrometer as a potential follow-on to the Atmospheric Infrared Sounder (AIRS) [2].

### A. NASA Instrument Incubator Program

Ball Aerospace & Technologies Corp. (BATC) is responsible for executing SIRAS-G, was one of nine, but the only industry-led proposal selected for the third Instrument Incubator Program (IIP) solicitation in 2002. IIP was established as a mechanism to develop of innovative technology suitable for future space-borne Earth Science Enterprise (ESE) programs and as a means to demonstrate and assess the performance of these instrument concepts in ground, airborne, and engineering model demonstrations. The goals set forth for an IIP program are to (1) develop and demonstrate mission development in less than thirty-six months; (2) develop the technology such that it is suitable for integration in an operational space instrument within eighteen months following the 3-year IIP development; (3) the instrument concepts developed under IIP must reduce instrument and measurement concept risk to allow the concept to be competitive in an Earth Science Enterprise Announcement of Opportunity; and (4) the concepts shall enable new science and/or reduce instrument cost, size, mass and resource use.

### B. SIRAS-G Overview

The SIRAS-G IIP effort will focus on advancing the SIRAS instrument concept to be ready for insertion into future Earth Science. While the SIRAS-G technology demonstration instrument is primarily intended as a laboratory demonstration, it our intent to build the instrument in a sufficiently robust manner to be upgradeable to airborne flight. In addition, as part of this effort, a series of engineering studies will be conducted to demonstrate the applicability of SIRAS-G to critical earth remote sensing needs.

One of the key benefits offered by SIRAS-G is the improved spatial resolution it offers for future sounders while simultaneously providing high spectral resolution. This will allow more opportunities for clear sky measurements in the absence of a microwave instrument; a crucial factor in

improving the yield of retrieved cloud-free scenes that can be assimilated into Numerical Weather Prediction (NWP) models. As an example, on the current Low Earth Orbit (LEO) AIRS instrument, it is estimated that only 4.5% of fields observed over oceans exhibited less than 0.6% cloud contamination [3]. This is largely attributable to the relatively large footprint of AIRS (13.5-km). SIRAS-G is being designed for a 4-km footprint from GEO. SIRAS-L (for LEO) has a 0.5-km footprint. Therefore, we would expect a significant improvement in the percentage of cloud-free scenes from SIRAS-G.

### C. Science Measurement Requirements

SIRAS-G is being developed to address several high priority research areas identified in NASA's ESE Research Strategy for 2000-2010. High spectral and spatial resolution makes it broadly applicable to a wide range of future missions. Research topics that SIRAS-G is targeted toward include:

*How are global precipitation, evaporation, and the cycling of water changing?*

SIRAS-G will make measurements similar to those currently being made by AIRS but from GEO. It will provide measurements of atmospheric temperature and water vapor, cloud properties, and land and ocean skin temperatures, with the accuracy and spectral resolution required for numerical weather prediction models. The goal is for SIRAS-G to provide significantly more rapid revisit time (6 minutes regional) and higher spatial resolution (4-km compared to 13.5-km for AIRS). These enhancements are aimed at addressing weather forcing factors on shorter time scales. Without synergistic microwave instruments, SIRAS-G will require ancillary data from the National Center for Environmental Prediction (NCEP), the European Center for Medium Range Weather Prediction (ECMWF) or other surface analysis data to retrieve cloud properties. Such retrieval methods have been developed by the AIRS Science Team as contingency algorithms to be used in case of ASMU failure. SIRAS-G offers a pathway to providing a continuous long-term data set complementary to that currently being provided by AIRS.

*What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?*

The ability of SIRAS-G to provide simultaneous observations of the Earth's atmospheric temperature, ocean surface temperature, and land surface temperature, as well as humidity, clouds, and the distribution of atmospheric trace gases enables SIRAS-G to provide a single data set that can be used to understand the horizontal and temporal changes in column abundances of important minor atmospheric gases such as CO<sub>2</sub>, CO, CH<sub>4</sub>, and N<sub>2</sub>O. This capability is potentially greatly enhanced by combining SIRAS-G with a high spectral resolution (0.05 – 0.1 cm<sup>-1</sup>) instrument such as

the Imaging Multi-Order Fabry-Perot Spectrometer (IMOFPS) [4].

*What are the consequences of climate and sea level changes and increased human activities on coastal regions?*

SIRAS-G provides high spectral resolution in the atmospheric window regions in the infrared, and will be able to observe the surface temperature in these regions with minimum atmospheric absorption. This can prove to be particularly useful in coastal regions where higher atmospheric water vapor amounts may be present. With the higher spatial resolution offered by SIRAS-G, there is a higher probability of finding cloud-free regions near the coastline than with larger footprint instruments such as AIRS or the NPOESS Cross-track Infrared Sounder (CrIS).

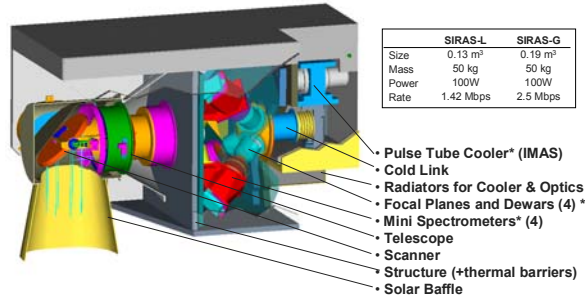
### D. Application to Future Earth Science Missions

One of the stated objectives of the IIP is to determine the potential impact of the technology on future Earth Science Enterprise (ESE) programs. There are at least four possible future ESE programs that would benefit from the technology developed under this IIP. The biggest advantage in SIRAS over other systems comes in its ability to improve the spatial resolution of these future sounders, allowing more opportunities for clear measurements while observing cloudy scenes.

*AIRS Follow-on:* The first potential future application is a follow-on system for the AIRS instrument currently lying on Aqua. AIRS provides global measurements of water vapor and temperature from LEO at high resolution and accuracy. SIRAS was originally designed to meet all the requirements of AIRS but in a significantly smaller system.

As we learn more about AIRS and assimilation of data by the weather forecasting community, we realize that clouds significantly degrade the ability to achieve accurate retrievals. We project that future sounding systems will require greatly enhanced spatial resolution. We now have designs for SIRAS that offer spatial footprints of less than 0.6 km (as compared to AIRS at 13.5 km) without sacrificing SNR. These systems are used in "pushbroom" scan mode to preserve the integration time. One drawback of these systems is that the wide field coverage is not achieved. We envision that the instrument configuration will have a pointing mirror to allow observations cross-track of critical weather phenomenon. Enhancements to the SIRAS-G optical system to accommodate the wider spatial field of view as being explored under the SIRAS-G IIP are a natural advancement of the system using the full potential of the aft-optics.

*Hyperspectral Environmental Sounder:* The second potential application is the sounder for the Hyperspectral Environmental Suite (HES). This is the next generation geosynchronous infrared atmospheric sounder for providing environmental data for operational meteorological analyses and weather forecasts. It is anticipated that the requirements for next generation IR sounding from geo-synchronous orbit



\* Common Spectrometer, FPA, Dewar, and Cooler Design for LEO or GEO

Fig. 1. The SIRAS-G Instrument Concept. Major instrument accommodation parameters are listed for GEO and LEO versions.

can be met with the SIRAS spectrometer and are being used as the baseline requirements configuration studies with SIRAS-G. With the spectrometer 1-mr IFOV, we currently estimate <10 km resolution with a 100 mm (4x magnification) aperture and < 5 km with an 200 mm (8x magnification) aperture. The latter is more suitable to the current HES encircled energy requirements. Since SIRAS-G has no moving parts in the spectrometer, requires no transforms to obtain spectra, and uses proven AIRS spectrometer technology and data processing algorithms, the SIRAS concept is potentially much smaller, lighter and uses less power than other proposed systems for this application. The instrument concept is shown in Fig. 1.

**ASTER Follow-on:** The third future application that can benefit from the SIRAS technology is for land thermal imaging. Follow-on missions to the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) mission will require improved atmospheric correction that can be achieved with an optimized version of one of the four SIRAS-G spectrometers. Currently an enhanced spatial resolution instrument concept to perform ASTER type observations has been developed. This instrument concept carries a single SIRAS spectrometer to accompany a larger high-resolution thermal imaging multi-spectral instrument. The SIRAS atmospheric correction system is of similar spatial resolution to the LEO sounder of approximately 0.6 km.

**Tropospheric Atmospheric Chemistry Mission:** Key measurement objectives for a Tropospheric Chemistry Mission would include observations of ozone, aerosols, and important atmospheric trace gases such as CO, CH<sub>4</sub> and NO<sub>x</sub>. The combination of SIRAS-G derivative and a multi-channel high-resolution spectrometer such as the IMOFPS [4], a multi-channel version of which is shown in Fig. 2 and being developed under BATC IR&D funding, could provide these measurements in a compact, solid-state instrument suite. IMOFPS consists of three co-bore sighted correlation spectrometers for determining vertical profiles of CO and column amounts of CO<sub>2</sub> and CH<sub>4</sub>. The addition of a fourth spectrometer channel for measuring NO<sub>x</sub> would provide a

tracer of motion and cloud detection. A two-channel version of SIRAS-G, one channel extending from 12.3- $\mu$ m to 15- $\mu$ m and a second centered at the 9.6- $\mu$ m ozone band, with spectral resolution “tuned” appropriately in both channels, will provide measurements of atmospheric temperature, water vapor and ozone column. All instruments in this suite again have no moving parts, except for a scene selecting scan mirror. For in-flight calibration, the scan mirror would periodically view on-board blackbody calibration sources and cold space.

## II. INSTRUMENT TECHNOLOGY

### A. Results from SIRAS-1999

In 1999, the NASA JPL-lead SIRAS [1] team undertook the development of an advanced instrument concept as a potential replacement for AIRS. This instrument concept is referred to as SIRAS-L (for SIRAS-Low Earth Orbit). This effort was funded under the first IIP (IIP-1999). The original SIRAS-1999 instrument concept was designed to meet the requirements of AIRS, but in a smaller package and with improved spatial resolution (0.5-km vs. AIRS 13.5-km). As part of this effort, a high-resolution infrared imaging spectrometer operating in the 12–15.4 $\mu$ m spectral region was designed, built and subsequently tested at cryogenic temperatures in a laboratory environment. A detailed study of the size, mass, and power of a SIRAS-L (Low Earth Orbit) instrument configuration was performed. In addition, it was demonstrated that the same spectrometer could meet the requirements of a GEO sounder.

A system concept, meeting the AIRS measurement requirements yet with enhanced spatial resolution, was developed that included scanning, passive and active cooling systems, the infrared spectrometers, fore-optics and the focal plane arrays. Reductions in subsystem complexity achieved through modular design, the use of standard format FPAs, and low-order gratings results in significant cost saving when compared to AIRS.

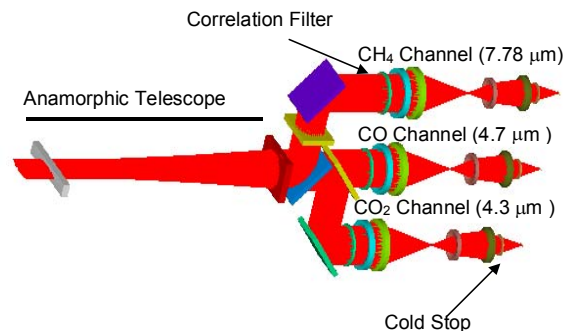


Fig. 2. Imaging Multi-Order Fabry-Perot Spectrometer (IMOFPS) provides enhanced high-resolution spectroscopy well suited for trace gas measurement. A combined SIRAS-G/IMOFPS instrument suite has the potential to provide targeted measurements of key trace gases and atmospheric parameters in a compact package.

TABLE 1

PRELIMINARY DESIGN PARAMETERS FOR SIRAS

Parameter		Spectrometer Number			
		1	2	3	4
$\lambda_{\min}$	( $\mu\text{m}$ )	3.7	6.2	8.8	12
$\lambda_{\max}$	( $\mu\text{m}$ )	4.61	8.22	12	15.4
$\lambda/\Delta\lambda$ Avg. Sampling		2200	2200	2200	2200
$\lambda/\Delta\lambda$ Avg. Resolution		1100	1100	1100	1100
Ruling	( $\mu\text{m}$ )	8	14	10	13
Order	(-)	2	2	1	1
$\lambda_{\text{blaze}}$	( $\mu\text{m}$ )	8.31	14.42	10.40	13.70
Incidence Angle	(deg)	45	45	45	45
Avg. Disp	(rad/ $\mu\text{m}$ )	0.2677	0.1534	0.1082	0.0832
Field of View	(deg)	13.957	17.752	19.844	16.201
Detector IFOV	(mr)	0.500	0.500	0.500	0.500
Slit IFOV	(mr)	1.000	1.000	1.000	1.000
EFL	(cm)	5.00	5.00	5.00	5.00
F-Number	(-)	1.70	1.70	1.70	1.70
Aperture Size	(cm)	2.94	2.94	2.94	2.94
Resolution.	(mr)	0.1723	0.2991	0.4314	0.5683
Detector Size	( $\mu\text{m}$ )	25	25	25	25
No. Channels	(-)	487	620	693	566
Transmission	(-)	0.5	0.5	0.5	0.5
FPA-Length	(cm)	1.22	1.55	1.73	1.41

The flight instrument concept developed in SIRAS-1999 has four spectrometer modules that cover the 3.4 to 15.4  $\mu\text{m}$  spectral region with the spectral bands broken out as shown in Table 1. A barrel scan mirror provides the ground coverage, and an all-reflective fore optic serves to focus the scene energy onto the slit. Scene energy is split into four separate spectrometer modules via beamsplitters. The need for low background noise required that the spectrometer modules be cryogenically cooled to 140 K, and the focal planes to 60 K. Active cooling of the detectors was proposed for the flight instrument configuration using a split-Stirling pulse-tube cooler

A laboratory demonstration spectrometer was developed to demonstrate that key performance requirements could be achieved. The longest wavelength spectrometer (Spectrometer 4 in Table 1) was built since it represented the greatest challenge from the standpoint of design, manufacture, and test. In keeping with the IIP objectives, this spectrometer was built to its flight configuration.

The SIRAS-1999 laboratory demonstration unit and its major components are shown in Fig. 3. The spectrometer measures 10 x 10 x 14 cm and weighs 2.0 kg. For the purposes of laboratory measurements, a PV HgCdTe

multiplexed detector array was provided on loan from the AIRS program. All hardware development and testing was performed at BATC. The major optical components are broken out into three subsystems: the collimator, the grating, and the camera. The most challenging optical system was the camera. This fast (F/1.7) optical system required near diffraction-limited performance over a fairly wide field-of-view (16.2 degrees). On SIRAS-1999, the following features of the SIRAS spectrometer were demonstrated:

- Optical quality and spectral resolution consistent with the required resolving power ( $\lambda/\Delta\lambda$ ) between 900 and 1400;
- Optical transfer function (spatial performance) required for system to perform as an accurate radiometer in the presence of high scene contrast (referred to as the Cij requirement on AIRS) was achieved;
- Demonstrated that the high optical throughput required meeting the NE $\Delta$ T requirement could be achieved;
- Demonstrated a spectrometer system of significantly reduced size, weight, and volume but of comparable performance to that of AIRS.

Spectrometer-level testing was performed in a thermal vacuum chamber at cryogenic temperatures. Thermal sources were viewed through a zinc selenide window and included a collimator and source assembly for spatial performance tests, and a blackbody for radiometric performance testing. Spectral measurements were made by adjusting the air path length between the test dewar and the blackbody and measuring the CO<sub>2</sub> absorption features.

Fig. 4 shows the results of the air path test. The data were analyzed for spectral resolution by comparing them to theoretical atmospheric transmission spectra for a 3-meter path length with varying spectral response widths. The response widths were varied until the resulting convolved modeled spectra matched the measured spectra. The results show that the SIRAS-1999 spectral resolution is  $1200 \pm 300$ . The entry point on SIRAS-1999 IIP was TRL 3. On completion, the spectrometer was at TRL 5.

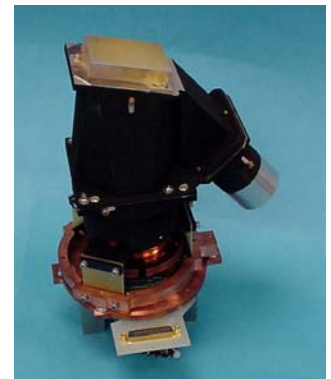
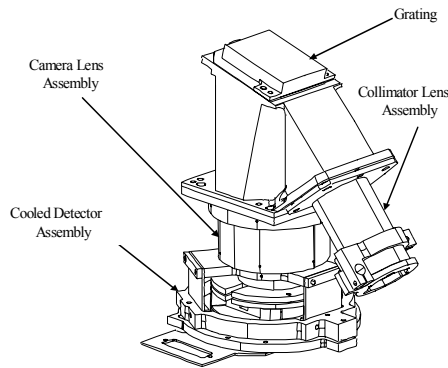


Fig. 3. SIRAS-1999 IIP spectrometer design (left) and as-built configuration (right).

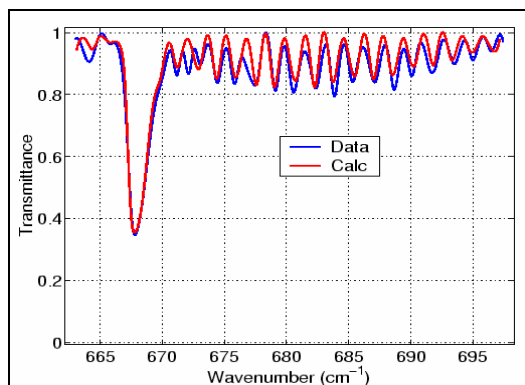


Fig. 4. SIRAS measurements of laboratory air confirmed that desired spectral resolving power ( $\lambda/\Delta\lambda$ ) between 900 and 1400 was achieved.

### B. SIRAS-G Laboratory Demonstration Instrument

A major focus of the SIRAS-G program is developing a technology demonstration instrument. A conceptual version of this instrument is shown in Fig. 5. The objective of IIP is, in general, to retire the risk of key technologies needed for next generation Earth Science Enterprise missions. The goal is to save flight program costs and schedule delays by developing technologies to their flight configuration well in advance of program needs. The SIRAS-G technology demonstration is aimed at specifically addressing these concerns.

Fig. 5 shows the overall SIRAS-G architecture and indicates the modules being developed on the SIRAS-G technology demonstration instrument. The strategy is to develop one layer of the instrument from telescope to digital data from the FPA electronics, with a goal of demonstrating the performance capability of SIRAS-G. One spectrometer assembly consisting of Grating Spectrometer 1 (i.e., Table 1) will be developed in the flight mechanical configuration to allow accurate sizing of the system. The Optically-Enhanced Cryogenic Dewar is part of this system. All remaining subsystems are not critical technology development challenges.

The SIRAS-G spectrometer assembly is being developed at BATC in Boulder, Colorado. Rockwell Scientific Corporation (RSC) in Camarillo, California will develop the FPA, clock, bias and A/D conversion electronics under subcontract. The FPA and electronics will be integrated with the spectrometer in Boulder. While the SIRAS-G spectrometer is largely based on the SIRAS-1999 spectrometer, it differs in that it is an imaging spectrometer with an appreciable spatial FOV. We are developing the technology demonstration instrument for a large format FPA (1024 x 1024 pixels) to provide high spatial resolution imaging capability and high spectral. This instrument will provide spectral sampling of approximately  $1.4 \text{ cm}^{-1}$  in 512 spectral channels ranging from  $3.35$  to  $4.5 \mu\text{m}$ . Primary emphasis has been placed on minimizing key image defects, particularly spectral smile and keystone distortion which are limited to less than 0.10 pixels over the entire FPA.

Active cooling of the aft optics and the FPA dewar will be demonstrated as well. A two-stage BATC Model-232 Sterling Cycle cooler has been made available for this demonstration. The BS-235 cooler is optimal for SIRAS-G FPA and optics cooling, being mass and power efficient, and exhibiting high cooling capacity. The BS-235 cooler mass is 10.5 kg, comparing favorably to the 37 kg AIRS cooler.

Performance testing of the spectrometer assembly for response across the field will be conducted. The spectrometer assembly will then be integrated with a laboratory-grade telescope with an aperture compatible with GEO sounding. The entire system including telescope, spectrometer and FPA will be tested for radiometric response in the laboratory. A measurement of the Earth's atmosphere will also be made by viewing the sky via relay mirrors to the outside. These systems-level tests will occur in Year 3 of the program.

### C. Optically-Enhanced Dewar Development

Focused effort on the development of the Optically-Enhanced Cryogenic Dewar (OECD) is a key part of SIRAS-G. This subsystem is designed to reduce the thermal heat load required for maintaining the FPA at cryogenic temperatures. For sake of comparison, the AIRS focal plane is shielded from viewing dewar walls via a cryogenic coldshield with an effective absorbance of 1.0 and an effective area of  $20 \text{ cm}^2$ . The radiation load into the AIRS coldshield is over 75 mW. For the SIRAS-G instrument, four smaller dewars replace the single AIRS dewar, each with a much simpler focal plane. This greatly simplifies the spectrometer and dewar design, but potentially multiplies the cold shield loads by up to a factor of four to 300mW. The OECD replaces the four high absorption coldshields with warmer (dewar-temperature) IR mirror assemblies. These warm shield assemblies cause the focal planes to view themselves at 60K rather than viewing a large coldshield. The area of each focal plane assembly with high absorptance is thus reduced from  $20 \text{ cm}^2$  to less than  $0.5 \text{ cm}^2$ , and the radiation loads are reduced proportionately.

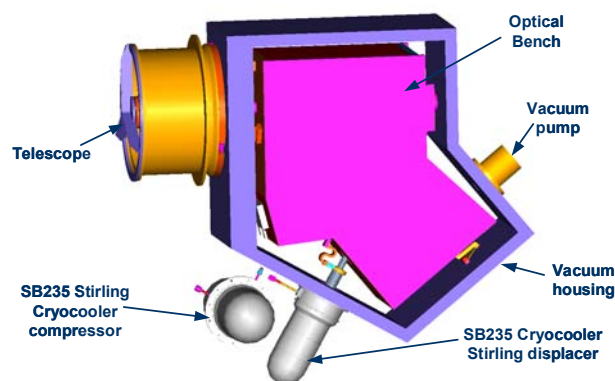


Fig 5. SIRAS-G Technology Demonstration Instrument – Conceptual Design. Major subsystems making up this assembly are identified.



With the OECs, we predict an overall load reduction of nearly 300 mW, which equates to about 18 watts of cooler input power (at 60W/W), or about 23 watts of instrument power (allowing for 80% conversion efficiency in the cooler electronics). For a system total power of about 100W, this is more than a 20% savings. Testing of an OECD prototype is planned for 2005.

#### IV. AIRBORNE DEMONSTRATION

The SIRAS-G technology demo is intended for laboratory demonstration. However, it is recognized that airborne flights of SIRAS-G would provide the opportunity for actual science measurements on field campaigns, science algorithm development and the potential for cross-validation with other airborne spectroscopic instruments. As such, we continuously strive to design and assemble the SIRAS-G technology demo in a manner suitably robust for airborne operation. For example, since the entire aft-optics bench must be maintained at cryogenic temperatures (160 K), we house this assembly in a self-contained vacuum enclosure. The SB-325 cryocooler has sufficient to provide all necessary temperature control and refrigeration needed to maintain the aft-optics bench at 160K and the FPA at 60K. In a similar manner, all components of the SIRAS-G technology demo are mounted onto a single instrument palette ensuring that the instrument maintains alignment even when removed from the laboratory. Thus, the SIRAS-G technology demonstration instrument is largely autonomous and readily adaptable to a variety of potential airborne platforms.

##### A. Pathway to Space

The instrument technology being developed under the SIRAS-G program has clear pathways to space, being suitable for a number of missions already identified as key in improving our understanding of climate and weather forecasting. The principal technical challenge is in demonstrating that sufficient control on image degrading errors such as spectral smile and keystone distortion can be achieved through design, fabrication and assembly such that the spectral response functions are not degraded over the entire FOV. The AIRS instrument has already demonstrated the feasibility of this approach. We aim to improve on this success with SIRAS-G. Our goal is to provide an instrument of lower mass, volume, and ultimately, lower cost, with enhanced capabilities including improved spatial resolution and greater flexibility afforded by modular spectrometer assemblies.

#### V. SUMMARY

NASA's support of independent technology development for future Earth science needs is a positive step forward offering promising benefits in terms of early identification of appropriate technologies and retiring technical risks. Technology developed under IIP will lead to reduced mission development cycle time and reduced overall cost, and ultimately, to more frequent science missions at lower overall cost. SIRAS-G exemplifies this goal, and represents an advance in high-resolution IR atmospheric sounding much needed for observation from geosynchronous orbit. The SIRAS-G grating architecture is well suited to a wide variety of high priority NASA ESE missions, both from GEO and LEO, and therefore is an instrument architecture well suited for next-generation missions aimed at providing continued atmospheric data for long-term climate change research. The further realization that the combination of SIRAS-G with other innovative instrument concepts, such as IMOFPS, offers a path to smaller more capable instruments for future ESE missions needs to be appreciated as well. IIP provides the mechanism to move SIRAS-G from concept to hardware demonstration, improving its technology readiness to where it will be ready for insertion into future spaceborne missions. Key to this is the successful completion and testing of the hardware demonstration instrument.

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